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Perspectives for the expansion of new renewable energy sources in Brazil

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ABSTRACT

The aim of this article is to show the opportunities for penetration of new renewable energy sources into the Brazilian energy mix, enabling it to continue generating a high quantity of clean energy compared to the world average. Different scenarios for the evolution of such sources in Brazil and in the world were analyzed within the 2010–2030 horizon. The study showed not only the benefits brought by these sources in terms of GHG emission avoidance but also the impact in terms of employment creation and the public investment necessary to obtain such benefits.

Contents

1. Introduction

Recent studies published by the International Energy Agency—IEA [1,2] have shown that penetration by a wide variety of renewable source technologies will be needed to meet the challenges of sustainable energy development. It is noted that many countries have made major progress in promoting renewable sources in their energy mixes. Nevertheless, the economic and technological obstacles are sizeable, demanding great efforts by governments.

Renewables still contribute relatively little to electricity generation in the world at the present time. In 2005, according to IEA data, the share was 18% of total production, including hydroelectric generation, but excluding traditional biomass. This scene should change in coming years as some of these technologies (especially wind generation) are seen to be rapidly reaching the commercialization stage. Others (such as solar), despite their great potential, still require major efforts in terms of R&D to reduce costs.

Brazil presents a very different picture. The power sector is hydrothermal, characterized by the strong presence of hydroelectric dams, large reservoirs with pluri-annual regularization, located in different river basins and distant from consumers. For this reason the system is connected by long transmission lines (see Fig. 1). The hydraulic capacity is complemented by thermal, nuclear, and wind power generation.

Abbreviations: GHG, Greenhouse gases; SIN, National Grid System; ONS, National System Operator; BEN, National Energy Balance; *CMG*, Levelized cost; *CI*, Investment cost per MWh of generated power; *CO*, Operating cost per MW h of generated power; $CV_{O\&M}$, Variable cost of operation and maintenance; C_{comb}, Fuel cost; P_{comb}, Fuel price; *HR*, Heat rate; CI_{idc}, Investment cost with interest during the construction period; *OC*, Overnight cost; D_n, The percentage of disbursement in year *n*; $CF_{O\&M}$, Fixed cost of operation and maintenance; *CA*, Annualized cost; PCC, Pulverized coal combustion; CSP, Concentrated solar power; PV, Photovoltaic; PCH, Small hydro power plant; SE, System Southeast/C.East; S, System South; NE, System Northeast; N, System North; PDE, Decennial Energy Plan; PNE, National Energy Plan; WEO, World Energy Outlook; CME, Marginal Expansion Cost; TP, Technical progress; CGE, Computable General Equilibrium

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The National Interconnected System (Sistema Interligado Nacional—SIN) is operated by the National System Operator (Operador Nacional do Sistema Elétrico—ONS), which manages the SIN in order to optimize the use of all sources. This is not a simple task because it relies on hydro power plants. It formulates operation strategies to consider all combinations between reservoir levels and hydrologic trends (state variables), as well as hydraulic and operating constraints for each planning period (stage). The problem is stochastic as the outcome is not static in time. Fig. 2 shows that producing more hydroelectricity can end up being cheaper, however, if it does not rain, there will probably be a power shortage owing to the very low reservoir storage level which could result in increasing future costs. On the other hand, were more thermal power to be produced and rain to exceed expectations, it would then be necessary to outflow water storage, and thereby waste energy [3].

According to the National Energy Balance (Balanço Enegético Nacional)—BEN 2010 [4], Brazil had an installed capacity of about

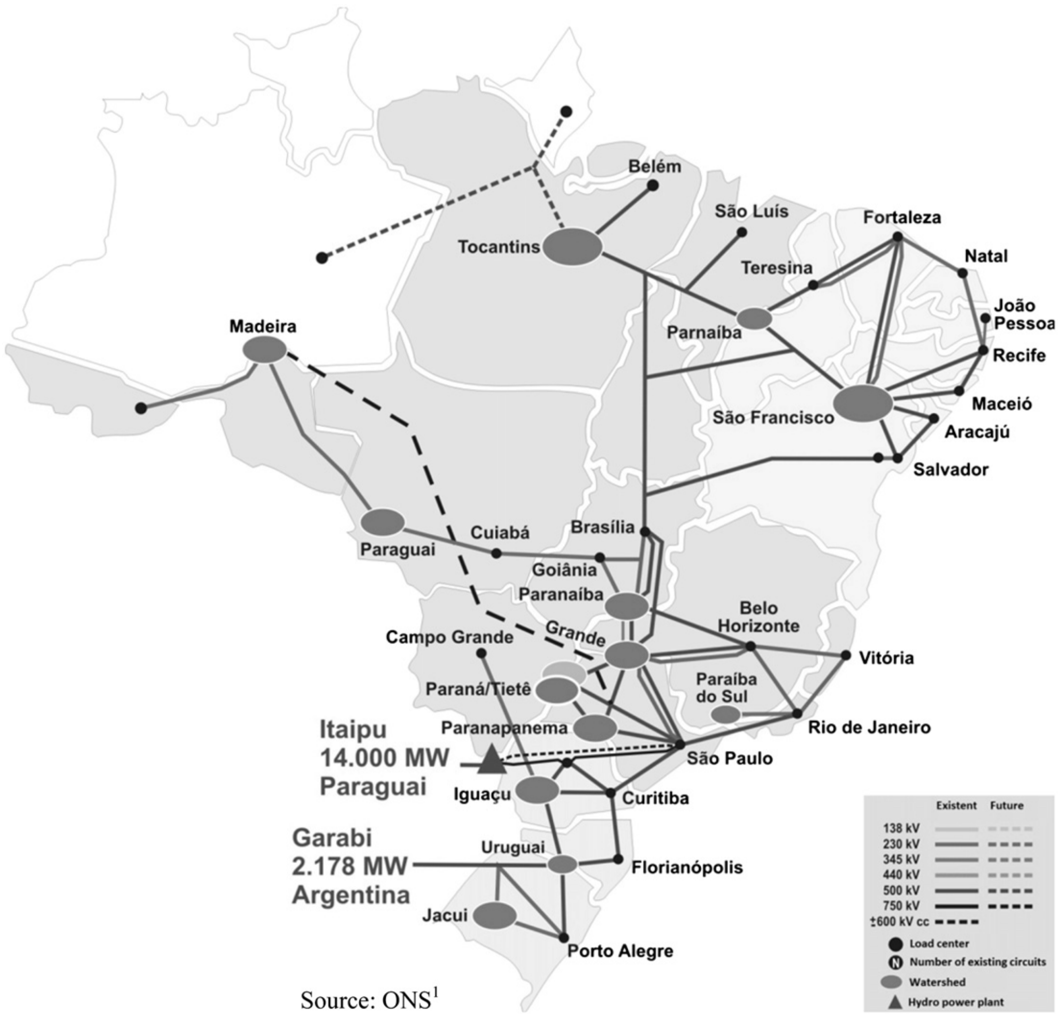


Fig. 1. National Interconnected System (SIN).
Source: ONS (Available online at www.ons.org.br/conheca_sistema/pop/pop_integracao_eletroenergetica.aspx).

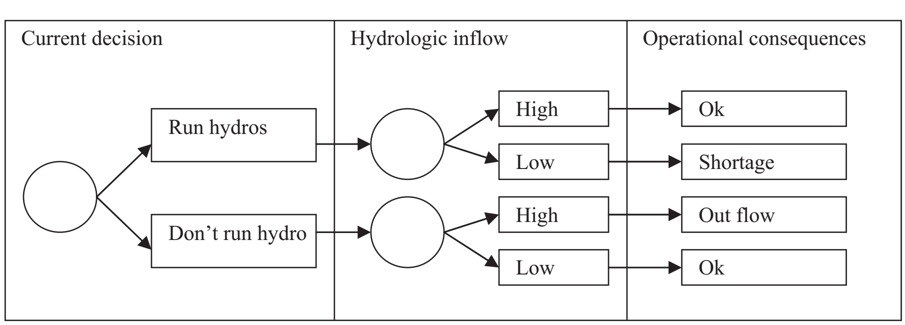


Fig. 2. Operational consequences of hydro generation.
Source: [3].

106 GW, of which more than 79 GW is hydropower, 24 GW thermoelectric, 2 GW nuclear and 602 MW wind.

This configuration keeps the greenhouse gas emissions (GHG) of the electricity sector at a relatively low level. This profile, however, could change considerably depending on the growth of electricity demand, the availability of resources for generation, environmental constraints and the cost of exploiting these resources.

The country, however, has been showing signs of commitment to the maintenance of a high share of renewables in the power sector, having implemented several mechanisms for the promotion of these sources, as can be seen in Pereira Jr. et al. [5].

Additionally, in November 2009, the President of the Republic announced a significant commitment to voluntarily reductions of greenhouse gas emissions (GHG). In accordance with this measure, the country is to achieve a reduction of between 36.1% and 38.9% of emissions by 2020. The emission avoidance actions proposed provide for initiatives in the areas of land use, animal husbandry, energy and the steel industry. In absolute terms, the reduction is estimated at about 1 billion tons of CO_2 equivalent in 2020.

In the energy sector, the reduction could be between 6.1 and 7.7%, with a focus on energy efficiency measures, increased use of biofuels, and the expansion of hydropower energy, bioelectricity and wind power.

These emission reduction estimates were presented to the international community at the 15th Conference of the Parties—COP 15 of UNFCCC, held in Copenhagen. On December 29, 2009, Law 1287 was enacted establishing a National Policy on Climate Change and making mandatory, under article 12, the previously announced estimates of emission reductions, incorporating them in the Nationally Appropriate Mitigation Actions—NAMAs of UNFCCC. Similarly, Article 6 of this Law makes the plan an instrument for the implementation of National Policy.

With this context in mind, the objective of the present study is to examine the development of renewable sources in Brazil with the aim of checking the possibilities for the penetration of renewable sources in the electricity sector within the 2010–2030 time-horizon. The benefits that such sources can bring in terms of GHG emission avoidance and job creation will be also evaluated, as well as the required public investment.

2. Analysis of the competitiveness of renewable sources

The analysis of the competitiveness of power generation sources will be based on the official databases of institutions such as the Energy Research Company (Empresa de Pesquisa Energética—EPE)[1], the National Petroleum, Natural Gas and Biofuels Agency (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis—ANP), the International Energy Agency—IEA and the U.S. Department of Energy—EIA/DOE. Particular attention will be given to checking such technical and economic data as operation and maintenance cost, investment cost, construction time, useful life, payback period, heat rate, power potential, and the capacity factor, among others. Based on this data, the average generation cost of each technology will be calculated, allowing accurate comparison between them.

The methodology used to calculate levelized cost is the same as that adopted in the "Projected Costs of Generating Electricity: 2005 Update" study [7]. This approach is in fact standardized to facilitate comparisons. For the same reason, taxes and charges in the industry will not be considered.

[1] This study gives a complete picture of the Brazilian energy sector. Some of the main data and results of this study can also be seen in [6].

Costs will be expressed, whenever possible, in Reais (R$). When conversion is necessary the exchange rate of 1.80 R$/US$ will be used.

Other important information for this study is the discount rate considered, since it shows the return on investments in electrical power generating plants. A thorough evaluation of the sector is needed to determine of this rate. There are lots of discussions about the discount rate which best represent the return on investment in the sector. Usually, the government adopts 12% per year in its energy planning. However, as the interest rate has been dropping during the last decade, the government has understood that the discount rate should be lower and has adopted 8% per year. Other sectors which supply energy sources for the power sector, such as, sugar-cane bagasse and oil products have higher opportunity cost, therefore, the discount rate for them should be in excess of 12% per year. Thus, to cover all these situations, three different discount rates will be used. A 12% rate will be assumed in the sections that present the scenarios.

The average generation cost (*CMG*) is expressed in R$/MW h and is calculated as follows:

$$CMG = CI + CO \tag{1}$$

where *CI* is the investment cost per MW h of generated power; and *CO* is the operating cost per MW h of generated power.

CO is composed of the variable cost of operation and maintenance—O&M ($CV_{O\&M}$) plus the cost of fuel (C_{comb}). This in turn is given by the fuel price (P_{comb}), in business unit, multiplied by the corresponding heat rate (*HR*). Thus:

$$CO = CV_{O\&M} + C_{comb} \tag{2}$$

so that

$$C_{comb} = P_{comb} HR$$

To obtain *CI* in the unit required, it is necessary to annualize the total investment. Typically, the investment cost of a plant is determined by the value of the installed kW, without considering the interest incurred during construction (*overnight cost*). Before annualizing the cost of investment it is therefore necessary to take in to account the interest during construction (*idc*) and bring all disbursements to present value.

$$CI_{idc} = OC(D_n(1+i)^{-n} + D_{n-1}(1+i)^{-(n-1)} + \ldots + D_1) \tag{3}$$

where, CI_{idc} is the investment cost with *idc*; *OC* is the overnight cost; D_n is the percentage of disbursement in year *n*; *i* is the discount rate; *n* is the number of years that disbursements occur

The resulting value must be added to the fixed cost of O&M ($CF_{O\&M}$), since this is reported with the same unit cost of investment as *idc*. The annualized cost (*CA*) will therefore be shown thus:

$$CA = (CI_{idc} + CF_{O\&M}) POT\{i(1+i)^T / [(1+i)^T - 1]\} \tag{4}$$

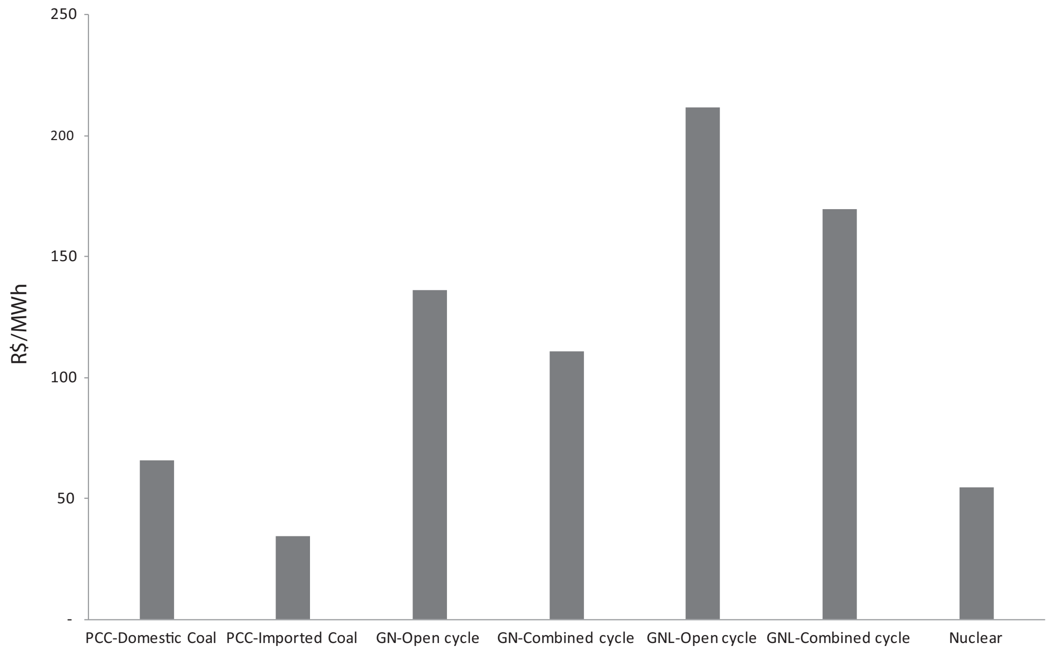
where *POT* is the power of the plant and *T* is the useful life of the project

Using these values it is easy to obtain the *CI*, dividing the *CA* by the plant's average annual generation (in MW h), which can be estimated by the average capacity factor (*FC*) of the plant

$$CI = CA / (FC.POT.8760) \tag{5}$$

This method enabled the obtaining of the technical and economic data necessary to calculate the average generation costs of the following technologies:

a. Domestic coal fired power plant (pulverized coal combustion—PCC),
b. Imported coal fired power plant (pulverized coal combustion—PCC);
c. Natural gas open cycle power plant:



Graph 1. Fuel costs.
Source: EIA/DOE [8], IEA [2], EPE [9].

d. Natural gas combined cycle power plant;
e. Thermonuclear generation III;
f. Biomass fired power plants—retrofit;
g. Biomass fired power plants—greenfield;
h. Biogas;
i. Wind power onshore;
j. Wind power offshore;
k. Photovoltaic;
l. Concentrating solar power (CSP);
m. Large hydro power plants (installed capacity exceeding 1000 MW);
n. Medium hydro power plants (installed capacity between 30 and 1000 MW);
o. Small hydro power plants—PCH (installed capacity below 30 MW); and
p. Transmission lines.

It should be noted that the average cost of additional generation provided by the expansion of transmission was not calculated, despite the savings resulting from interconnecting different hydrographic basins, since such technology does not generate energy. However, as huge hydro power plants are located far from the load center, the price of transmission lines is usually incorporated in these projects. Therefore, transmission line expansion is determined by the government and thus does not represent a bottleneck for energy supply in Brazil.

In the case of thermoelectric plants, fuel costs were reckoned in US$/MW h, as shown in Graph 1. In the case of natural gas plants, generation cost is based on the use of LNG, which is 55% more expensive than dry natural gas. Fuel cost was estimated at 7 US$/MMBtu to maintain compatibility with the data presented in Table 1.

Domestic coal considered in US$/ton, unit in which it is usually traded[2] , is actually less expensive than imported; however, since the calorific value of the imported coal is far greater than that of the domestic, the $/MWh generation cost with the latter is higher than with the imported.

No change in fuel prices was estimated, since it is assumed that the relationship between them will remain fairly constant over time. The capacity factor presented in Table 1 represents the values estimated in studies on the Brazilian power sector, such as EPE's [9]. According to its analysis, as the system will continue to rely on hydro power plants, it is reasonable to consider that the capacity factor of the power plants will not change considerably during the time horizon of this study, because additional plants play the role of complementing hydro power generation.

Graph 2 shows the results in terms of average generation cost for the technologies analyzed using different discount rates, 8%, 12% and 16% (full equity).

The large and medium hydroelectric plants are the cheapest technologies in Brazil. Onshore wind, biomass, sugar-cane and PCH are already becoming competitive when compared with natural gas-fired and coal, assuming an 8% discount rate, which is the one commonly used in the planning of expansion of generation by the government [10].

The results also clearly show that the more capital-intensive plants, such as hydro, nuclear, wind and solar, are more sensitive to discount rate changes. On the other hand, the average generation cost of natural gas plants is little affected since they are more intensive in variable costs. The country's macroeconomic conditions may thus affect the expansion of its generation capacity. Graph 3 presents the composition of costs of each source, using an annual discount rate of 12%.

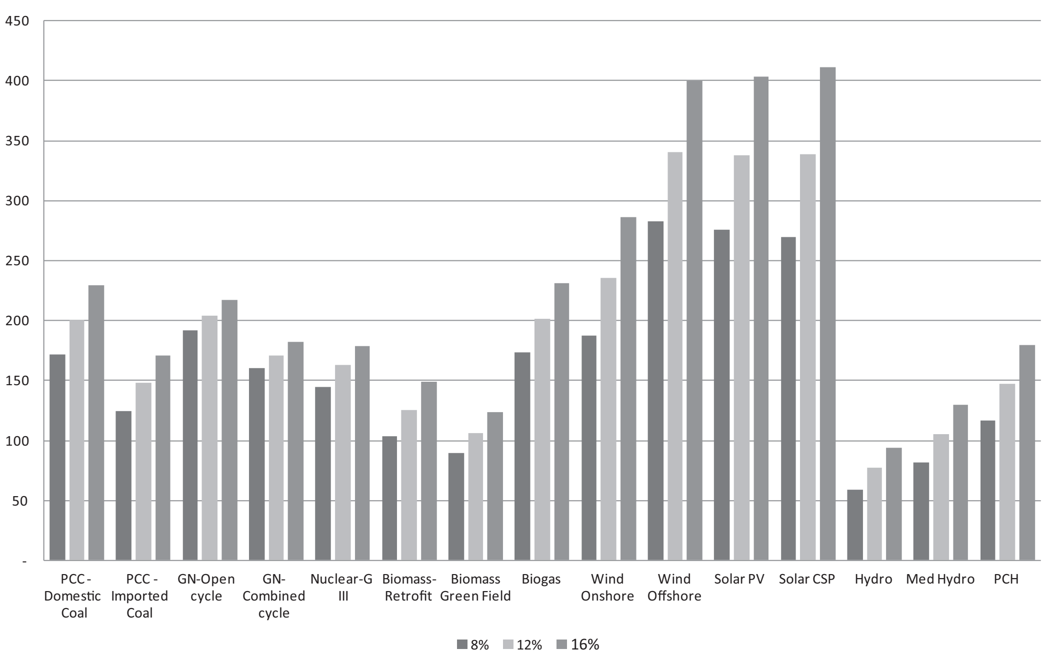
3. Reference scenario

The energy model used for the elaboration of the reference scenario was MESSAGE (Model for Energy Supply System Alternatives and Their General Environmental Impacts). This model

[2] The cost of domestic Candiota coal is estimated at approximately 40 R$/t, while that from South Africa is quoted at 70 US$/t. The exchange rate used was 1.80 R$/US$.

Table 1
Technical–economic data of the plants.
Source: EIA/DOE [6], IEA [2], EPE [7].

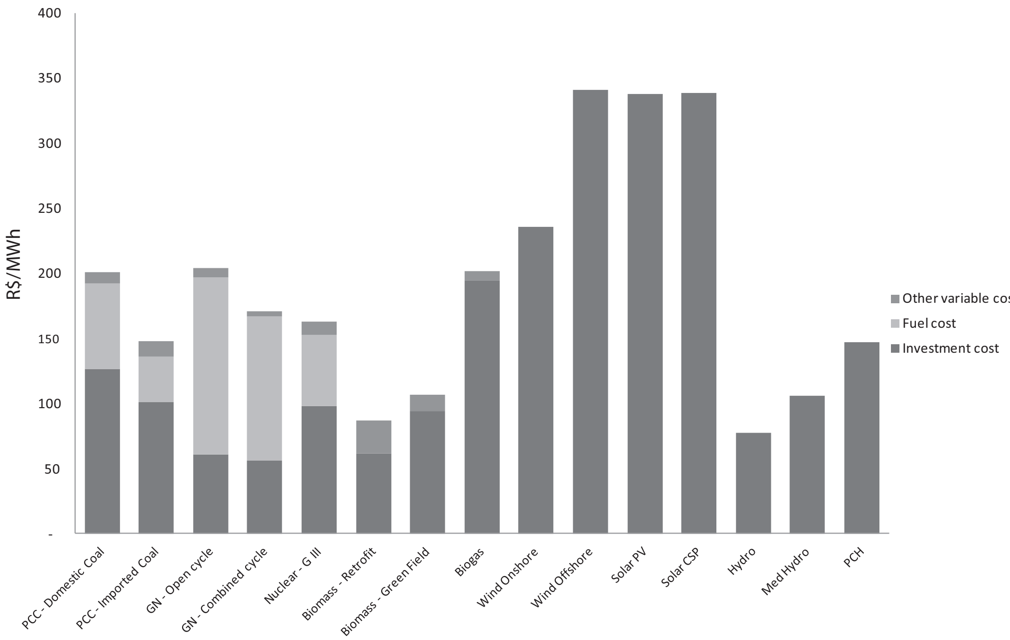
Technology	Power total (MW)	Capacity factor (%)	Fixed cost O&M (US$/kW-year)	Variable cost O&M (US$/MW h)	Heat rate (Btu/kW h)	Construction period (years)	Useful life (years)	Investiment cost (US$/kW)
PCC—national coal	600	40	28	4.7	10,350	4	35	2100
PCC—imported coal	600	50	28	7.0	9200	4	35	2100
GN—open cycle	250	40	12	4.0	10,800	2	20	850
GN—combined cycle	500	60	18	2.3	8800	3	20	1200
Nuclear—G III	1000	85	92	0.6	10,500	6	40	3500
Biomass—retrofit	100	67	10	14.0	9450	2	20	1500
Biomass—green field	100	67	65	7.0	9800	2	20	1900
Biogas	30	50	169	–	13,650	2	20	2400
Onshore wind	50	30	31	–	–	2	20	2500
Offshore wind	100	30	87	–	–	3	20	3500
Solar fotovoltaic	100	40	12	–	–	2	20	5900
Solar CSP	5	20	58	–	–	3	20	4800
Large hidroelectric	1000	50	29	–	–	6	50	1800
Medium hidroelectric	300	55	29	–	–	3	50	2100
PCH	30	50	29	–	–	2	50	2600
Transmission	1000	–	23	5.0	–	1	25	1500



Graph 2. Average generation cost.
Source: Authors.

was originally developed at IIASA (International Institute for Applied System Analysis) for the optimization of an energy system (with its supply and demand). The IAEA acquired the latest version of the model and several updates have been made, especially the introduction of a user-friendly interface to facilitate its implementation.

The mathematical principle of MESSAGE is the optimization of an objective function subject to a set of constraints that define the feasible region which contains possible solutions to the problem. The value of the objective function helps to choose the best solution, in accordance with a specific criterion, which is usually the minimization of cost. In a more general classification, MESSAGE is a mixed integer programming model (which allows some variables to be defined as integers), used for the optimization of a power system. The model was designed to formulate and evaluate alternative strategies for the supply of energy, in line with restrictions such as investment limitations, availability and price of fuels, environmental regulation and market penetration rates for new technologies, among other factors. Environmental aspects can be evaluated, accounting for and, if necessary, limiting emissions of pollutants for different technologies at various levels of the energy chain. This facilitates assessment of the impact that



Graph 3. Composition of generation costs.
Source: Authors.

environmental regulations will have on the development of the energy system.

Information in the model is presented thus:

- Variables: flows, production capacities and inventories; and
- Restrictions: balance of flows (extraction, conversion, transmission, distribution, end use), limits (absolute or relative) for the activities, dynamic (intertemporal) and accounting.

The demand for electricity (final energy) in each subsystem (Southeast/C.East—SE, South—S, Northeast—NE, North—N) was assumed to be exogenous and regarded as an input for the MESSAGE simulations. The values were estimated based on the projections of the Ten-Year Energy Plan (Plano Decenal de Energia—PDE) for the period 2010–2020, and the National Energy Plan (Plano Nacional de Energia—PNE) for the remainder of the horizon. Table 2 shows the electricity demand data used in this study.

The subsystems are currently connected by extensive transmission lines and form the National Interconnected System—SIN which serves approximately 98% of electricity demand in the country. The areas not covered by the SIN are called Isolated Systems. For this study the Madeira River hydroelectric plants were considered as part of the Southeast/C.Oeste subsystem, since the energy from these plants is almost entirely directed to that subsystem. The plants in the Tapajós River and the Belo Monte were considered part of the North sub-system.

In relation to demand (final energy) for petroleum and natural gas derivatives use outside the electricity sector, the projections used were taken from the ‘‘Development First: Linking Energy and Emission Policies with Sustainable Development’’ study recently prepared for the URC (UNEP Research Centre on Energy and Environment) under the ‘‘Development First’’ project. It is estimated in the present study that the demand for natural gas (except for the electricity sector) will grow at the rate of 6.8% per year until 2030, while growth of demand for derivatives will be 3.8% per year in the same period.

Table 2
Estimated electrical energy demand—TWh.
Source: Authors, based on [7,8].

	SE	S	NE	N	Total
2010	298	81	73	38	491
2015	371	99	93	64	627
2020	450	121	117	84	771
2025	538	146	145	106	936
2030	638	175	176	134	1.123

The following plants were considered as candidates to meet the projected demand for electricity in this study: hydro, small hydro, coal, natural gas, oil, nuclear, sugar-cane bagasse, biogas, wind and solar CSP. The possibility of expanding transmission lines for energy exchange between the subsystems was also considered. The expansion of the generation park, corresponding to the reference scenario, was obtained using MESSAGE simulations (Table 3).

In order to check the consistency of the results, the reference scenario was compared with other recently published studies (see Table 4), such as PNE 2030 and World Energy Outlook (WEO), by the International Energy Agency [1].

The expansion of generating capacity in Brazil shown in the WEO study is much smaller because the rate of economic growth adopted in the time horizon of the study was 3% per year, whereas in the present work and PNE 2030 it is approximately 4%. In relation to PNE 2030, the main difference lies in the expansion of wind, which was not considered competitive with other sources at the time the plan was prepared. The penetration of this source in the present scenario reduced dependence on natural gas (in the comparison with PNE) and required more complementarity of the dams.

The marginal cost of the expansion forecast (CME) in this study is presented in Table 5.[3]

It was found necessary to adopt an alternative methodology for determining CME because of problems in planning expansion,

Table 3
Capacity expansion (MW).

	Hydro	Natural gas	Coal	Nuclear	Oil	Biomass	Wind	PCH	Total
2010	80,476	7734	2015	2007	1942	5300	7800	5000	112,274
2015	103,895	7734	3815	3507	1942	6500	12,000	6500	145,893
2020	137,910	8734	7815	3507	1942	7500	15,000	7500	189,908
2025	163,610	13,734	8815	3507	1942	7500	17,000	8500	224,608
2030	170,345	17,734	8815	3507	1942	8500	19,000	8500	238,343

Table 4
Comparison with other studies (MW).

Technology	Simulation	PNE 2030	WEO
Hydro	170.3	156.3	103.7[a]
Natural gas	17.7	21.0	25.3
Coal	8.8	6.0	5.1
Oil	1.9	2.9	4.6
Nuclear	3.5	7.3	6.1
Biomass	8.5	6.4	7.6[b]
Wind	19.0	4.6	7.6
PCH	8.5	7.7	–
CSP	–	–	1.1
Total	238.3	211.7	161.5

[a] Includes PCH.
[b] Includes biogas.

Table 5
Marginal cost of expansion—CME (R$/MW h).

Year	CME
2015	120
2020	180
2025	200
2030	240

such as that adopted in the present study, since investment decision variables are not continuous, due to the indivisibility of power generation plant capacity, as shown by Andersson and Bohman [11]. This can result in solutions with excess supply or demand, making it impossible to obtain a CME of the model.

Some authors address the issue of determining CME through a peak-load pricing methodology based on the formulation of Williamson [12] and Turvey [13]. The problem with this approach is the need for adjustments to achieve the long-run equilibrium. As noted by Andersson and Bohman [11], the most appropriate methods for determining CME are those that derive from an optimization.

It is with this understanding that O'Neill et al. [14] propose an approach that addresses the problem of indivisibilities in determining the marginal cost in the electricity sector, based on the methodology for optimal allocation of resources proposed by Scarf [15].

The approach described by O'Neill et al. [14] models a static case of expansion of an electricity system with indivisibilities as a mixed integer programming problem, and then as linear programming, created from the solution of the antecedent problem. The idea is to expand the set of commodities (or continuous variables) in at least one additional continuous variable for each integer variable present in the problem.

A mixed integer programming problem with m continuous variables and n integer variables ($R_m \times Z_n$) that has an optimal feasible solution can thus be converted into a linear programming problem with $m+n$ continuous variables (R_{m+n}) with n additional linear constraints, each with a value equal to the optimal value of the integer variable. A linear programming problem that solves the mixed integer is thereby obtained.

The methodology is easily applied in existing energy models, such as MESSAGE, and generates CME results that correctly indicate the expansion of the system.

[3] The CME is an important value which indicates the expansion requirements and allows evaluating the technologies with reasonable costs as shown in Graph 2.

4. Alternative scenarios

Alternative scenarios were elaborated based on projected reductions of investment costs for power generation technologies using renewable sources. These projections were based on learning curves estimated by the International Energy Agency.

The learning curve[4] is a concept that denotes the relationship between unit cost and cumulative output in stable processes, suggesting that the cost of inputs or time per unit of output decreases to a fixed percentage each time the level of production doubles. The roots of this concept go back to studies that showed more than a century ago that individual performance increases with acquired experience.

Wright [16] introduced this concept into the industrial environment by demonstrating that the decrease in direct labor costs would fall by 20% every time cumulative production doubled in the aeronautical construction sector.[5] Since the publication of that study, similar results have been shown to occur in the case of small groups, organizations and industries (see [17]).

Learning curves enable the drawing up of norms for long term improvement and help answer questions related to improving productivity and its limitations. The equation describing the curve is as follows:

$$C(X) = aX^{-E} \tag{6}$$

where $C(X)$ is the unit cost that varies in function of the cumulative production X. Parameter a is a constant which can be determined by the cost and by the initial production. The term E, known as the experience parameter, characterizes the slope of the curve and represents the technological progress made possible by the gain of experience in the production process. The relationship between the rate of technical progress (TP) and the experience parameter is given by

$$TP = 2^{-E} \tag{7}$$

The definition of a rate of technical progress cannot be done arbitrarily but is a function of the production process itself. It is, after all, reasonable to assume that the improvement of a process

[4] The associated literature also uses the following terms: experience curve; learning by doing; and learning by use.

[5] Although the 20% cost reduction for every doubling of production has been used as rule for many industries, caution is required in its application since the rate may differ even for similar productive sectors within companies and for orders of the same product within the same production plant.

stems from its gradual change, which aims at eliminating existing limitations.

Such initiatives often require investments able to increase the productive capacity and skills of workers through training, and the updating of machinery and infrastructure, in order to raise the productivity of manpower.

The above-mentioned outlays should be genuinely aimed at improving the processes. Additionally, incentive mechanisms can be created to accelerate the process of technical improvement and thereby increase the *TP*.

According to Costa et al. [18], most countries with significant installed capacity of renewable sources have incentive instruments to subsidize the generation costs of such technologies properly and efficiently. Such mechanisms, in addition to increasing *TP*, aim to stimulate and increase the share of renewables in their energy grid, justified by issues of energy security and climate change.

In Brazil the feed-in tariff has already been adopted by PROINFA (Incentive Program for Alternative Sources), a program which faced some difficulties in achieving its goals. The energy auctions aimed at promoting renewable sources, on the other hand, were very successful and, each year, have achieved better results in terms of reducing the cost of traded electricity. [6] It is therefore assumed in this paper that energy auctions will continue to be used throughout the time horizon considered.

Regarding the learning curve for the technologies considered in this work, it was assumed that biomass, biogas and small hydro power plants are already competitive compared to traditional generation sources, and will therefore not need incentive programs.

Technologies that should benefit from mechanisms to promote renewable sources are onshore and offshore wind, and solar PV and CSP. The International Energy Agency estimates the cost levels of investment needed for these technologies to reach the commercial stage and year in which this cost is reached based on projections using learning curves.

By this means, an estimate can be made of the evolution of these costs based on the projection of the expansion of each of these technologies in the global reference scenario (current policies) World Energy Outlook (WEO), the International Energy Agency, as shown in Table 6.

As can be seen, onshore wind power is the only technology that reaches commercial stage before the end of the study time horizon. The offshore wind and solar PV reach this stage only in 2030. The solar CSP does not reach a commercial stage under this scenario.

WEO of the International Energy Agency presents two further alternative world scenarios, the *New Policies* and scenario 450, where a much bigger expansion of renewable sources is considered compared to the reference scenario, as shown in Table 7.

Since the alternative scenarios present more expansion it can be understood that the reduction in investment costs will also be greater, assuming the same rate of technological progress. In the *New Policies* scenario the reduction of investment costs is shown in Table 8

It can be seen that offshore wind reaches the commercial stage around 2025 and solar PV immediately after. Solar CSP, even in this scenario, does not reach the commercial stage. It only does so in scenario 450, as shown in Table 9.

Based on these investment cost projections, two alternative scenarios consistent with the *New Policies* and WEO 450 global scenarios were developed. Other hypotheses, however, have also been taken into account to make the alternative national scenarios more realistic.

[6] For a more detailed discussion of mechanisms for the promotion of renewable sources in Brazil see [5,18]

Table 6
Evolution of investment costs.
Source: Authors, based on IEA [2].

Technology	Investment cost (US$/kW)					Commercial stage (US$/kW)
	2010	2015	2020	2025	2030	
Onshore wind	1500	981	900	834	773	900
Offshore wind	3500	2121	1916	1751	1600	1600
Solar PV	5900	3312	2586	2217	1900	1900
Solar CSP	4800	2794	2677	2394	2141	1500

In the first scenario, it was considered that there would be no further expansion of coal fired generation after 2015. This hypothesis is consistent with the national reality, since Brazil adopted voluntary targets for the reduction of GHG emissions as part of the IPCC conference. Coal generation in this scenario is replaced by offshore wind. This scenario was called "Expansion without Coal." Table 10 presents the results.

The impact of such expansion was analyzed in terms of public spending, job creation and GHG emissions reduction. Public spending was taken to be the difference between the actual cost of investment and the said value at commercialization stage (see Table 8). The cost of investment is one of the MESSAGE model outputs.

In addition to reducing GHG emissions, another consideration for public spending on renewable energy is job creation. This information, however, is not easy to obtain and varies from technology to technology and depends on the country context. Therefore, some references were taken from available literature. To estimate job creation, data was considered from Table 11.

It may be noted from Graph 4 that there are, in this scenario, significant gains in terms of emission avoidance and job creation in relation to the reference scenario. The increase in government spending is only seen in the first period of the analysis. GHG emissions are reduced by between 20% and 30%, and job creation, by the end of the period, can exceed that of the reference scenario by up to 20%.

In the second scenario, it was considered that there would be no further expansion of fossil fuel generation after 2015. This hypothesis is also consistent with the national reality. In this case, however, the country would be taking more aggressive measures to reduce greenhouse gas emissions. Fossil fuel generation in this scenario would be replaced not only by offshore wind, but also by PV and CSP. This scenario was called "Expansion without Fossil Sources." Table 12 presents the results.

Although solar PV electricity generation only begins in 2025 in the SIN, it is understood that there may be significant expansion as well as distributed generation earlier. There will, however, be a need for suitable regulation to be introduced to make this feasible. The economic and environmental impacts in relation to the reference scenario are presented in Graph 5. In this case, the main impacts are seen to be in job creation, achieving well over 100% by the end of the period, and in GHG emission reduction, reaching 50% by the end of the period.

Graph 6 shows the result of the three scenarios built in this study and facilitates comparisons between them for the year 2030.

There are some other methodologies which help analyze mechanisms to promote renewable energy sources. Some of them adopt marginal abatement cost curves to compare different technologies in terms of GHG emission reduction (see [23,5]). The problem of these studies is that they analyze only one variable, the environmental matters. Some other studies use multi-criteria analysis or computable general equilibrium (CGE)

Table 7
Installed capacity (MW)—alternative scenarios WEO.
Source: IEA [2].

Technology	2020			2025			2030		
	Ref.	New policies	450	Ref.	New policies	450	Ref.	New policies	450
Onshore + Offshore wind	447	535	592	544	703	824	662	862	1148
Solar PV	101	110	138	144	197	259	206	294	485
Solar CSP	12	17	42	19	30	77	31	52	141

Table 8
New Policies scenario for evolution of investment costs.
Source: Authors, based on IEA [2].

Technology	Investment cost (US$/kW)					Commercial stage (US$/kW)
	2010	2015	2020	2025	2030	
Onshore wind	1500	981	839	755	697	900
Offshore wind	3500	2121	1764	1557	1418	1600
Solar PV	5900	3312	2492	1937	1629	1900
Solar CSP	4800	2794	2466	2158	1896	1500

Table 9
Scenario 450 evolution of investment costs.
Source: Authors, based on IEA [2].

Technology	Investment cost (US$/kW)					Commercial stage (US$/kW)
	2010	2015	2020	2025	2030	
Onshore wind	1500	981	807	710	624	900
Offshore wind	3500	2121	1684	1447	1243	1600
Solar PV	5900	3312	2259	1722	1312	1900
Solar CSP	4800	2794	1994	1729	1500	1500

model to incorporate not only environment, but also macroeconomic variables (see [24,25,26]). These certainly make the analysis more complete, however they require the development of complex models. This is the main advantage of the present methodology: it covers four different variables with a very simple approach. In future studies, this methodology can be improved by incorporating other variables such as those proposed by Budzianowski [27], who adopts five criteria to analyze the introduction of biogas-to-electricity in Poland's energy sector: CO_2 generation intensity; electricity production capacity; cost of electricity; perspectives for near-term deployment; and risks.

Table 10
Scenario expansion without coal (MW).

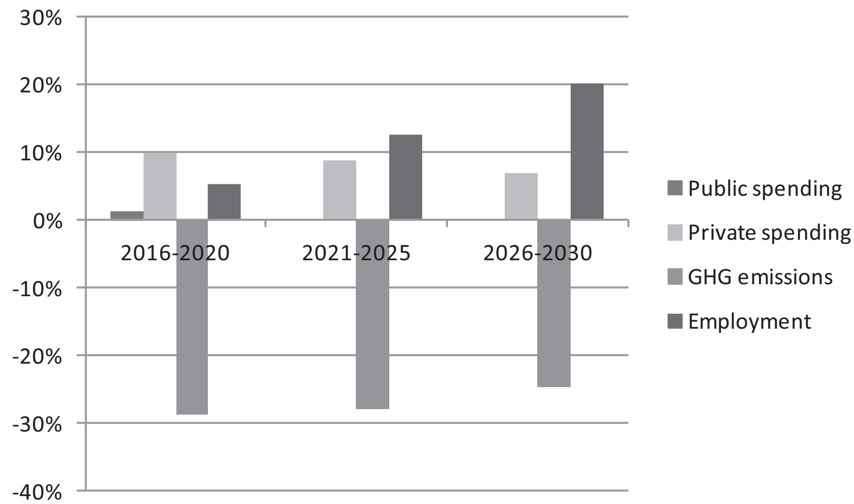
	Hydro	Natural gas	Coal	Nuclear	Oil	Biomass	Wind	PCH	Total
2010	80,476	7734	2015	2007	1942	5300	7800	5000	112,274
2015	103,895	7734	3815	3507	1942	6500	12,000	6500	145,893
2020	137,910	8734	**3815**	3507	1942	7500	**21,700**	7500	192,608
2025	163,610	13,734	**3815**	3507	1942	7500	**25,300**	8500	227,908
2030	170,345	17,734	**3815**	3507	1942	8500	**27,300**	8500	241,643

Table 11
Job creation.

Technology	Jobs/MW	Source
Large hydro	5.1	Navigant Consulting [19]
Medium hydro	6	Navigant Consulting [19]
Nuclear	3.72	Sioshansi [20]
Natural gas	1.1	INEEL [21]
Coal	1.24	Sioshansi [20]
Oil	1.24	Sioshansi [20]
PCH	6.5	Navigant Consulting [19]
Biomass	1.8	Sioshansi [20]
Onshore wind	2.9	Heavner & Del Chiaro [22]
Offshore wind	7.6	Heavner & Del Chiaro [22]
CSP	5.9	Heavner & Del Chiaro [22]
PV	7.26	Heavner & Del Chiaro [22]

5. Conclusion

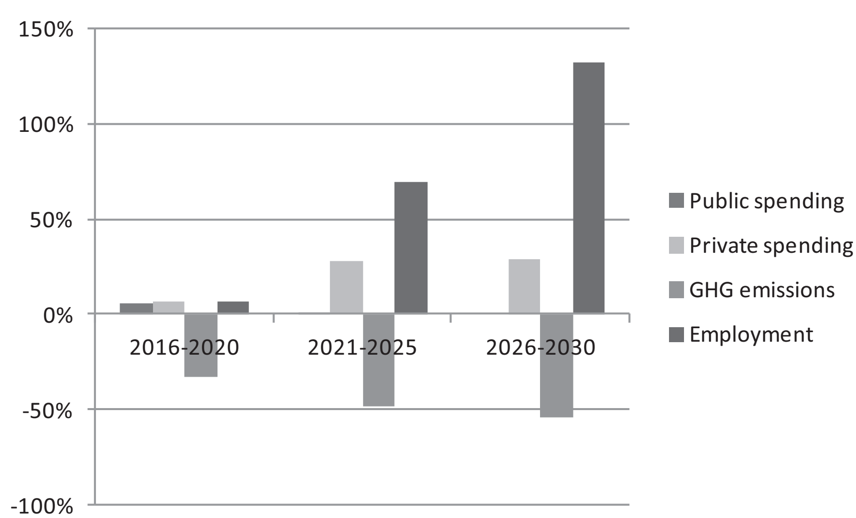
The aim of this study was to show the opportunities for penetration of new renewable sources in the national energy



Graph 4. Economic and environmental impacts: scenario expansion without coal.

Table 12
Scenario expansion without fossil sources (MW).

	Hydro	Natural gas	Coal	Nuclear	Oil	Biomass	Wind	Small hydro	PCH	CSP	Total
2010	80,476	7734	2015	2007	1942	5300	7800	5000	0	0	112,274
2015	103,895	7734	3815	3507	1942	6500	12,000	6500	0	0	145,893
2020	137,910	**7734**	**3815**	3507	1942	7500	**23,400**	7500	0	0	193,308
2025	163,610	**7734**	**3815**	3507	1942	7500	**27,000**	8500	**15,000**	0	238,608
2030	170,345	**7734**	**3815**	3507	1942	8500	**29,000**	8500	**20,000**	**5000**	258,343



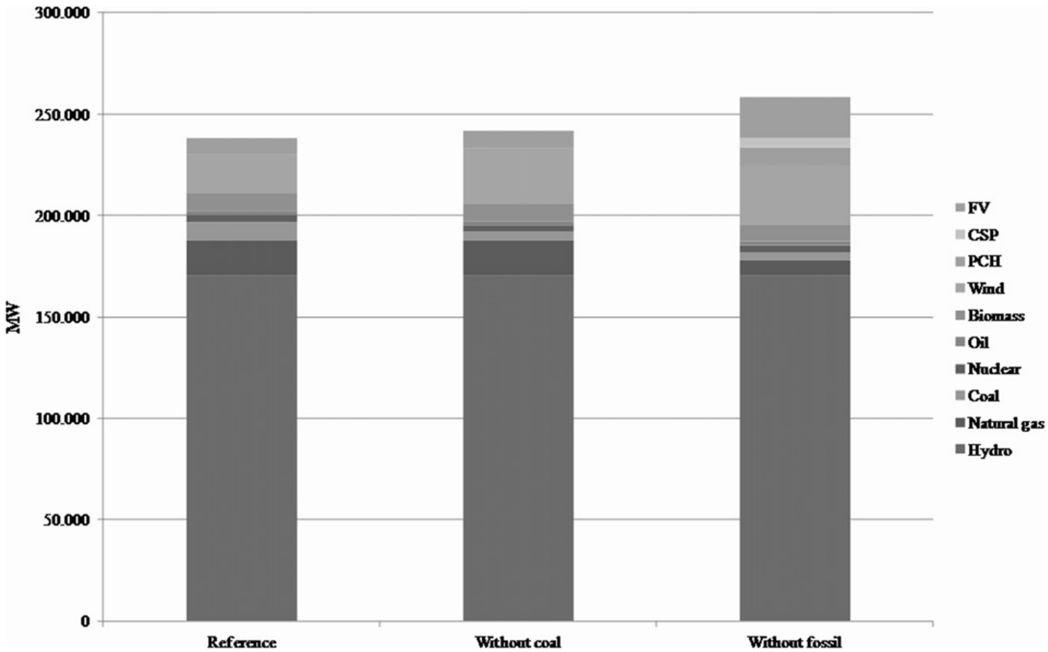
Graph 5. Economic and environmental impacts: scenario expansion without fossil sources.

mix, so that its principal characteristic, which is that of possessing clean generation compared to the world average, can be maintained.

Similar to other regions in the world, many renewable sources, such as hydro, biomass and, more recently, onshore wind, are competitive in the country. Offshore wind, solar PV and CSP would still need incentives. These technologies would require a major international effort as represented by the International Energy Agency *New Policies* and 450 scenarios to become economically feasible in Brazil.

Even then, significant additional government spending will be needed to enable the expansion of these renewable sources. In addition, the alternative scenario in which there is no expansion of coal fired generation has a CME 8% higher, on average, than the reference scenario (see Table 5). The scenario without fossil sources has a CME 10% higher than the reference scenario. That means that the impact on electricity tariffs would also be significant. On the other hand, there would be positive impacts in terms of job creation and greenhouse gas emission avoidance.

Finally, it is important to state that thermal power plants improve the quality of energy supply in the Brazilian power system because these technologies complement the generation of intermittent renewable sources like hydro, wind and solar power.



Graph 6. Results 2030.

Therefore, more technical analysis is necessary to verify the minimum generation required from thermal power plants.

References

[1] International Energy Agency—IEA. World Energy Outlook 2010. Paris: IEA; 2010.
[2] International Energy Agency—IEA. Energy Technology Perspectives 2010. Paris: IEA; 2010.
[3] Carpio LGT, Pereira Jr AO. Economical efficiency of coordinating the generation by subsystems with the capacity of transmission in the Brazilian market of electricity. Energy Economics 2007;29:454–66.
[4] Empresa de Pesquisa Energética—EPE. Balanço Energético Nacional 2010. Rio de Janeiro: EPE; 2011.
[5] Pereira Jr AO, Pereira AS, La Rovere EL, Barata MDL, Villar SDC, Pires SH. Strategies to promote renewable energy in Brazil. Renewable and Sustainable Energy Reviews 2011;15:681–8.
[6] Pereira Jr AO, Soares JB, Oliveira RG, Queiroz RP. Energy in Brazil: toward sustainable development? Energy Policy 2008;36:73–83.
[7] International Energy Agency—IEA. Projected Costs of Generating Electricity: 2005 Update. Paris: IEA; 2005.
[8] Energy Information Administration—EIA/DOE. Annual Energy Outlook 2010. Washington: EIA/DOE; 2011.
[9] Empresa de Pesquisa Energética—EPE. Plano Nacional de Energia 2030. Rio de Janeiro: EPE; 2007.
[10] Empresa de Pesquisa Energética—EPE. Plano Decenal de Energia 2020. Rio de Janeiro: EPE; 2011.
[11] Andersson R, Bohman M. Short- and long-run marginal cost pricing: on their allege equivalence. Energy Economics 1985;7:279–88.
[12] Williamson OE. Peak-load pricing and optimal capacity constraints under indivisibility constraints. The American Economic Review 1966;56:810–27.
[13] Turvey R. Optimal pricing and investment in electricity supply. Cambridge, MA: MIT Press; 1968.
[14] O'Neill RP, Sotkiewicz PM, Hobbs BF, Rothkopf MH, Stewart Jr WR. Efficient market-clearing prices in markets with nonconvexities. European Journal of Operational Research 2005;164:269–85.
[15] Scarf HE. The allocation of resources in the presence of indivisibilities. Journal of Economic Perspectives 1994;8:111–28.
[16] Wright T. Factors affecting the cost of airplanes. Journal of Aeronautical Science 1936;4:122–8.
[17] Argote L, Beckman SL, Epple D. The persistence and transfer of learning in industrial settings. Management Science 1990;36:140–54.
[18] Costa CV, La Rovere EL, Assmann D. Technological innovation policies to promote renewable energies: Lessons from the European experience for the Brazilian case. Renewable and Sustainable Energy Reviews 2008;12:65–90.
[19] Navigant Consulting, Job creation opportunities in hydropower, final report presented to US National Hydropower Association; 2009.
[20] Sioshansi FP. Renewable subsidies: do they create or destroy jobs? USAEE 2009;17:3.
[21] Idaho National Engineering and Environmental Laboratory—INEEL. "U.S. Job Creation Due to Nuclear Power Resurgence in the United States". INEEL/EXT-04-02384. Vol. 1. Idaho; 2004.
[22] Heavner B, Del Chiaro B. Renewable energy and jobs: employment impacts of developing markets for renewables in California. Environment California Research and Policy Center 2003.
[23] Oliveira LB, Henriques RM, Pereira Jr AO. Use of wastes as option for the mitigation of CO_2 emissions in the Brazilian power sector. Renewable and Sustainable Energy Reviews 2010:3247–51.
[24] La Rovere EL, Soares JB, Oliveira LB, Lauria T. Sustainable expansion of electricity sector: sustainability indicators as an instrument to support decision making. Renewable and Sustainable Energy Reviews 2010;14: 422–9.
[25] Lins ME, Oliveira LB, Moreira da Silva AC, Rosa LP, Pereira Jr AO. Performance assessment of alternative energy resources in Brazilian power sector using data envelopment analysis. Renewable and Sustainable Energy Reviews 2012;16:898–903.
[26] Timilsina GR, Shrestha RM. General equilibrium effects of a supply side GHG mitigation option under the clean development mechanism. Journal of Environmental Management 2006;80:327–41.
[27] Budzianowski WM. Can 'negative net CO_2 emissions' from decarbonised biogas-to-electricity contribute to solving Poland's carbon capture and sequestration dilemmas? Energy 2011;36:6318–25.